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Controls for microgrids with storage: Review, challenges, and research needs

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ABSTRACT

The interest on microgrid has increased significantly triggered by the increasing demand of reliable, secure, efficient, clean, and sustainable electricity. More research and implementation of microgrid will be conducted in order to improve the maturity of microgrid technology. Among different aspects of microgrid, this paper focuses on controls of microgrid with energy storage. A comprehensive review on current control technology is given with a discussion on challenges of microgrid controls. Basic simulation results are also presented to enhance and support the analysis. Finally, research needs and roadmap for microgrid control are also described.

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Contents

1. Introduction

The microgrid concept has been researched and implemented intensively by many experts worldwide with significant research conducted in U.S., E.U., Japan, and Canada [1,2]. The interest on microgrid increases due to its potential benefits to provide reliable, secure, efficient, environmentally friendly, and sustainable electricity from renewable energy sources (RES) [3]. Before the microgrid concept was introduced, many researches had been conducted on distributed generation (DG). Researchers soon realized that installing individual DG in power systems may create problems as many as it solves. Hence, microgrid concept was proposed to overcome those problems [4,5].

Research and implementation of microgrid have increased in last few years in several ways. Many aspects of microgrid ranging from architecture to controls have been researched and implemented in laboratory test-beds and field models. Indeed, this condition leads to more advanced development of microgrid. In accordance with the environmental awareness, technologies that support increasing renewable energy penetration in microgrids have become popular and important research topics. Microgrid research fits very well within smartgrid activities with specific emphasis on demand side management and there is need to outline ongoing research in microgrid to benefit the researchers and policy makers. Two topics closely related to these technologies are microgrid controls and energy

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storage applications in microgrid, which are addressed in this paper.

Section 2 gives an overview and definition of microgrids. Specific discussion on microgrid controls describing local, centralized, and decentralized controls have been presented in Section 3. Energy storage applications in microgrids are addressed in Section 4 and challenges of microgrid controls have been discussed in Section 5. Section 6 focus on simulations finally, Section 7 provides conclusion and research needs.

2. Microgrid review

A microgrids is an interconnection of distributed energy sources, such as microturbines, wind turbines, fuel cells and PVs integrated with storage devices, such as batteries, flywheels and power capacitors on low voltage distribution systems [6]. A basic microgrid architecture is shown in Fig. 1. This architecture is commonly known as the Consortium for Electric Reliability Technology Solutions (CERTS) architecture [7,8].

This microgrid consists of a group of radial feeders, which could be part of a distribution system or a building's electrical system. There are three sensitive-load feeders (Feeders A–C) and one non-sensitive-load feeder (Feeder D). The sensitive-load feeders contain sensitive loads that must be always supplied, thus each feeder must have at least a microsource rated to satisfy the load at that feeder. On the contrary, the non-sensitive-load feeder is the feeder that may be shut down if there is a disturbance or power quality problems on the utility; the non-sensitive-load feeder will be left to ride through the disturbance or power quality problems [7,8].

When there is a problem with the utility supply, Feeders A–C can island from the grid using the static switch that can separate in less than a cycle to isolate the sensitive loads from the power grid to minimize disturbance to the sensitive loads. In an islanded operation, a microgrid will work autonomously, therefore must have enough local generation to meet the demands of the sensitive loads [7,8]. Furthermore, a disturbance requiring a feeder to operate individually may also occur. If this latter case is considered in the microgrid design, each sensitive-load feeder must have enough local generation to supply its own loads while the non-sensitive-load feeder will rely on the utility supply.

Post-disturbance, the microgrid will reconnect to the utility and work normally as a grid-connected system. In this grid-connected, excess local power generation, if any, will supply the non-sensitive loads or charge the energy storage devices for later uses. The excess power generated by the microgrid may also be sold to the utility; in this case, the microgrid will participate in the market operation or provide ancillary services [6,9,10].

The disconnection or reconnection processes must be specified by the point of common coupling (PCC), a single point of connection to the utility located on the primary side of the transformer. At this point the microgrid must meet the established interface requirements, such as defined in IEEE standard 1547 series [11–17]. Furthermore, the successful disconnection or reconnection processes depend upon microgrid controls. The controllers must insure that the processes occur seamlessly and the operating points after the processes are satisfied [7,8]. More detail information about the microgrid controls will be explained in the next section.

The last main part of the CERTS architecture is the energy manager which is responsible to manage system operation through power dispatching and voltage setting to each micro-source controller. Some possible criteria for the microgrid to fulfill this responsibility are as follows [7]:

(1) insure that the necessary electrical loads and heat are fulfilled by the microsources;

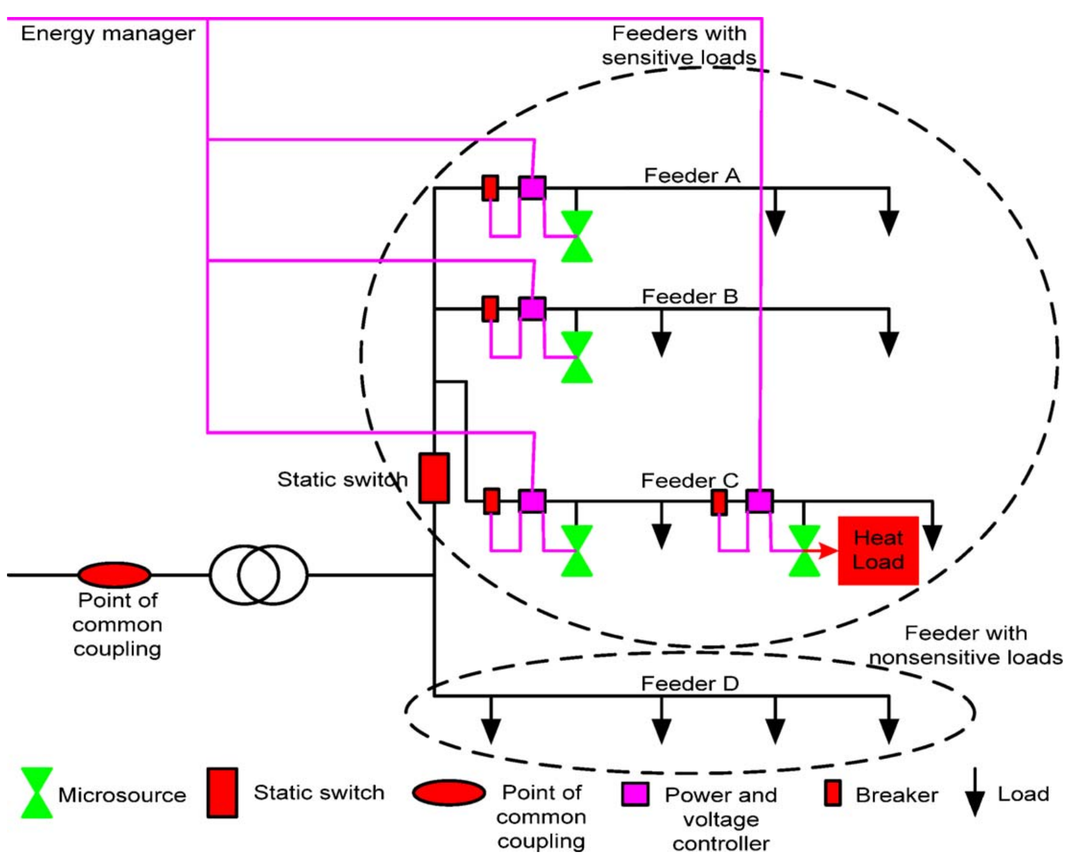

Fig. 1. Microgrid architecture.

(2) insure that the microgrid satisfies operational contracts with the utility;
(3) minimize emissions and/or system losses; and
(4) maximize the operational efficiency of the microsources.

Research on microgrid has reached not only software simulation level, but also laboratory test-bed and field model levels in past few years. The following are examples of test-beds for testing different components, control strategies, and storage technologies of microgrids [9,18]:

- a specially designed single phase system of the NTUA with agent control software,
- a general test site for distributed energy resources (DER), called DeMoTec at ISET,
- a flywheel test rig at the University of Manchester.

The increase interest on microgrids is triggered by the potential benefits of the microgrid that may provide reliable, secure, efficient, environmentally friendly, and sustainable electricity from RES [3]. A microgrid can improve reliability and security of power distribution system, especially for sensitive loads, because microsources will ensure that the sensitive loads will receive enough power in any operating condition. Different from function of a single distributed generator attached to a conventional distribution network, microsources will act as main power generation instead of standby power generation.

Power system efficiency may increase up to 90% if combined heat and power (CHP) is applied in the microgrid to utilize heat for local uses [19]. In addition, the efficiency increase can also result from loss reduction in transmission lines related to local power generation for local uses. Moreover, the local uses of local power generation will reduce energy or power density of transmission lines so that transmission line congestion can be reduced and investments on transmission line upgrade can be delayed [20,21].

Environmental friendliness can be achieved due to the current trend to increase the RES participations in microgrids; this participation increase will significantly reduce green house gas (GHG) emissions [22–26]. Furthermore, RES can also ensure energy sustainability due to the nature of their availability; RES can gradually substitute fossil fuels that have limited sources. Ideally, energy can be harvested at no cost, besides installation, operational, and maintenance costs, from RES. However, renewable energy is naturally intermittent so that an energy storage system is required to optimize energy utilization [3,27–32].

3. Microgrid controls

Microgrid controllers have responsibilities to ensure that [7]:

(1) microsources work properly at predefined operating point or slightly different from the predefined operating point but still satisfy the operating limits;
(2) active and reactive powers are transferred according to necessity of the microgrids and/or the distribution system;
(3) disconnection and reconnection processes are conducted seamlessly;
(4) market participation is optimized by optimizing production of local microsources and power exchanges with the utility;
(5) heat utilization for local installation is optimized;
(6) sensitive loads, such as medical equipment and computer servers are supplied uninterruptedly;
(7) in case of general failure, the microgrid is able to operate through black-start; and
(8) energy storage systems can support the microgrid and increase the system reliability and efficiency.

Based on the above responsibilities and the controller coordination, the microgrid controls can be classified as local controls, centralized controls, and decentralized controls. More detailed information about these controllers will be explained in this section.

3.1. Local controls

Local controls are the basic category of microgrid controls. The main usage of local controllers is to control microsources. This type of controllers is aimed to control operating points of the microsources and their power-electronic interfaces without communication systems. No communication systems result in simple circuitry and low cost. The measured data for local controllers are local voltages and currents [7,8]. In most microgrid applications, local controllers will coexist with other type of controllers, while in fully islanded microgrids, as described in [33–35], the local controllers are the only required controllers. The local controllers must also ensure the "plug-and-play" function of microsources; a or several microsources must be able to seamlessly connect to or disconnect from the distribution network when and where they are needed [36,37].

Most microsources require power-electronic interfaces to convert their output to suit power system specifications. The general model for a microsource is shown in Fig. 2. It contains three basic elements: prime mover, DC interface, and voltage source inverter (VSI). The microsource couples to the microgrid using an inductor. The VSI controls both the magnitude and phase of its output voltage, $\bar{V}$, in order to control real and reactive powers. The voltage regulation is crucial for a microgrid with integration of large number of microsources in order to overcome oscillation caused by high penetration of microsources. The voltage regulation is also used to insure that there are no large circulating reactive current between sources [7,8].

Besides the voltage regulation, microsources must also regulate active and reactive powers. The most common methods to regulate these powers are droop-based active and reactive power controls. These droop controls are scale-down versions of droop-based controls in utility. The droop-based controls consist of voltage-reactive power and frequency-active power droop controls [38,39].

The description of voltage-reactive power droop control can be seen in Fig. 3. As the reactive current generated by the microsource becomes more capacitive, the operating voltage will increase. Therefore the local voltage set-point is reduced to keep the voltage at or near its initial set-point. On the other hand, the local voltage set-point is increased if the reactive current becomes more capacitive. The limit of reactive current increase and decrease is defined by Q_{max}, which is a function of volt-ampere (VA) rating of the inverter and the power generated by the prime mover [7,8].

In a grid-connected operation, microgrid loads receive power both from the grid and from local microsources, depending on the customer's situation. If the grid power is lost because of voltage drops, faults, blackouts, etc., the microgrid can transfer smoothly to island operation. In addition, the microgrid is usually equipped with a capability to intentionally operate in islanded mode of

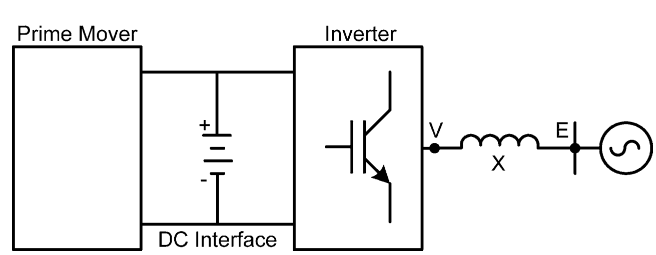

Fig. 2. General model of a microsource connected to a microgrid.

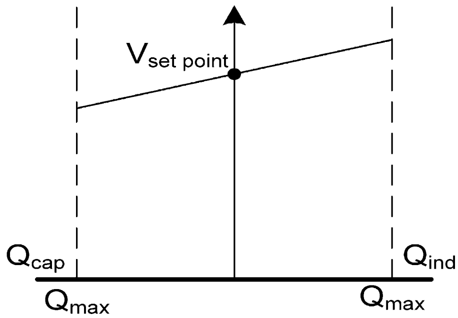

Fig. 3. Voltage set-point with droop.

operation [40]. With this capability, the microgrid can be islanded intentionally for specific reasons even though there is no disturbance or power quality problem in the utility side. After the separation of the microgrid from the main grid, the voltage phase angles at each microsource in the microgrid change, resulting in an apparent reduction or increase in local frequency depending upon the power mismatches. The local frequency will decrease if the microgrid receives power from the utility in grid-connected operation but will increase if the microgrid sends power to the utility in grid-connected operation [41]. The dependency of frequency on power allows each microsource to provide its proportional share of load without immediate new power dispatch from the Energy Manager.

An example of two microsources is shown in Fig. 4. In this example, the sources are assumed to have different ratings, $P_{1\ max}$, and $P_{2\ max}$. The dispatched power in grid mode (P_{10} and P_{20}) is defined at base frequency, ω_0. The droop is defined to insure that both systems are at rated power at the same minimum frequency. During a change in power demand, these two sources operate at different frequencies, which cause a change in the relative power angles between them. When this change occurs, the two frequencies tend to drift toward a lower, single value of ω_1. Unit 2 will have higher increase of its share of the total power needs than Unit 1. Each controller must have a restoration function to overcome the microgrid frequency decrease caused by droop regulation [7,8].

3.2. Centralized controls

Centralized controls of microgrids can be explained based on hierarchical controls in Fig. 5. In fact, hierarchical systems may have centralized or decentralized controllers. The control level of hierarchical systems can be classified as follows [10,42–44]:

- local controllers consisting of Microsource Controllers (MCs) and Load Controllers (LCs);
- Microgrid Cental Controllers (MGCCs); and
- Distribution Management System (DMS).

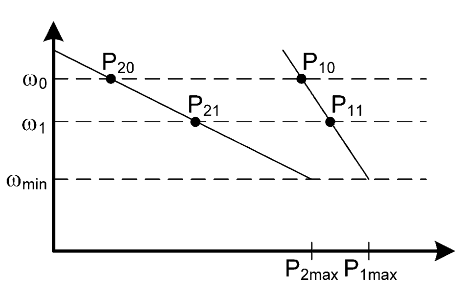

Fig. 4. Droop-based power-frequency control.

The MCs in centralized controls have similar principle as the local controllers discussed in Section 3.1. In centralized controls, The MCs may also be enhanced with various degrees of intelligence. In addition, LCs are installed at the controllable loads to provide load control capabilities. LCs are commonly used for demand side management [10].

For each microgrid, there is an MGCC that interfaces between the DMS and the microgrid. The MGCC may have different roles ranging from simple coordination of the local controllers to the main responsibility of optimizing the microgrid operation. The difference between centralized and decentralized controls is defined by the centralization roles assumed by the MGCC; the level of decentralization can vary depending on the share of responsibilities assumed by the MGCC and the MCs and LCs. In a centralized control, MCs and LCs follow the orders of MGCC during grid-connected mode and have autonomy to perform their own controls during islanded mode [10].

DMS or Distribution Network Operator (DNO), to which several MGCCs are interfaced, has responsibility to manage the operation of medium and low voltage areas in which more than one microgrid may exist. In addition, one or more Market Operators (MO) will exist in the system if the microgrids participate in market operation. DNO and MO are not parts of microgrids but representatives of the utility [10].

Centralized control is best used for microgrids with the following characteristic [10,45]:

- The owners of microsources and loads have common goals and seek cooperation in order to meet their goals.
- Small-scale micogrids may be feasible to control with the presence of an operator.

3.3. Decentralized controls

Decentralized controls have similar description to the centralized controls and can be explained based on Fig. 5. In decentralized controls, the main responsibility is given to MCs that compete to maximize their production in order to satisfy the demand and probably provide the maximum possible export to the grid taking into account current market prices. The decentralized control is aimed to maximize autonomy of the microsources and loads. Several intelligent methods based on peer-to-peer algorithm, such as multi-agent-based [9,46] and gossip-based algorithms [47], may be used for decentralized controls.

Decentralized control is best used for microgrids with the following characteristics [10]:

- microsources can have different owners in which case several decisions should be taken locally,
- microgrids operating in a market environment require that the action of the controllers of each unit participating in the market should have a certain degree of intelligence,
- local microsources may have other tasks besides supplying power to the local distribution networks, like producing heat for local installations, keeping the voltage locally at a certain level or providing a backup system for local critical loads in case of main system failure.

4. Energy storage systems for microgrid applications

As discussed earlier, microsources have small generating capacities and most microsources require inverters to convert their output to suit power system specifications [48]. Thus, the connections of small-size sources which are dominated by power-electronic-interfaced sources can be considered as an inertia-less system [38]. This inertia-less system cannot response to the initial

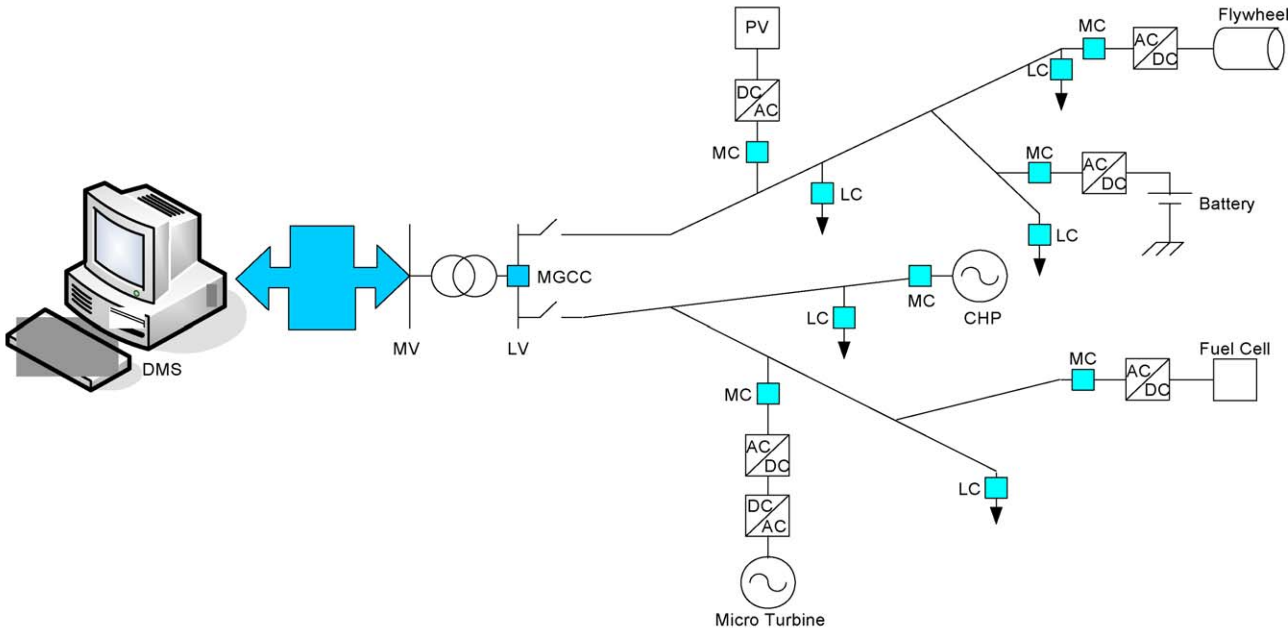

Fig. 5. Hierarchical control of microgrid.

or surge power or energy mismatch by using their machines' inertia as commonly found in bulk systems. Therefore, a microgrid requires energy storage systems to solve the mismatch problems [3,27–32].

Microgrids provide high opportunities to integrate small-scale RES into local power systems [34]. This integration will increase percentage of electricity produced from renewable energy sources to the overall electricity generations, hence will increase sustainability of electricity and ideally will also provide reliable, secure, flexible, affordable, and limitless electricity [3]. However, renewable energy is influenced by some environmental input parameters, and the energy produced from renewable energy sources may be inherently variable. Moreover, renewable energy is also naturally intermittent [27,30]. For instances, there are possibilities of fully cloudy or non-breezing day which relates to no energy produced from photovoltaic (PV) arrays or wind power plants. In addition, the connection of big amount of renewable energy sources to a local power system may cause a stability problem [28].

In order to utilize renewable energy optimally without having problems related to variability and intermittency of energy and also instability of electricity, a properly designed storage system must be implemented in a local power system containing big amount of small-scale RES. This optimal utilization can be fully competitive either technically or economically to the utilizations of energy from the best fossil fuels or nuclear technologies [30].

Owing to the facts that different renewable energy sources have different characteristics and the likeliness of hybrid energy sources in a microgrid, the design of versatile energy storage systems having capability to operate in wide ranges of power density and energy density is required. Since no single energy storage technology has this capability, system will incorporate combinations of technologies such as supercapacitors, batteries, superconducting magnetic energy storage (SMES), and kinetic energy storage in flywheels [31].

The capacity of the energy storage system depends upon the characteristics of compensation being provided. The type and capacity of energy storage used must be selected accordingly. In case of short-time voltage sag which may draw higher currents for only few cycles, an energy storage element with smaller storage may be employed. However, additional backup source may be employed if sag continues for longer time interval leading to interruption of supply depending on the critical load. In case of harmonics elimination and reactive power compensation, suitable passive filter may be employed, thereby reducing the rating of the energy storage system [49].

5. Challenges of microgrid controls

Microgrids installations and integration in LV distribution systems will increase significantly in future. Consequently, distribution systems will have different characteristics from the current conventional distribution systems. The difference will be more significant with increased number of microgrids. Thus, suitable control strategies must be designed to anticipate this difference [50].

Besides to optimize system operation electrically, microgrid controls also aim to optimize production and consumption of heat, gas, and electricity in order to improve overall efficiency [22]. Moreover, controlling a large number of microsources having different characteristics will be very challenging due to the possibility of conflicting requirement and limited communication [6]. In case of decentralized or centralized controllers, control action required with probable lost input parameters will be surely challenging.

Transitions from grid-connected to islanded modes of operation are likely to cause large mismatches between generation and loads, causing a severe frequency and voltage control problem. The ‘‘plug-and-play’’ capability may also create serious problem if the connection and disconnection processes involve big number of microsources at the same time [6].

6. Simulations results and discussion

The simulation diagram is given in Fig. 6. The microgrid consists of several microsources: a microturbine of 10 kVA, a wind turbine of 100 kVA and a PV array of 1 kW_p, and sensitive loads of 73 kW and 28 kVAR and non-sensitive loads of 100 kW and 40 kVAR. The non-sensitive load is placed between the distribution transformer and the breaker. In the islanded operation, the microgrid only supplies the sensitive loads while the non-sensitive loads will be

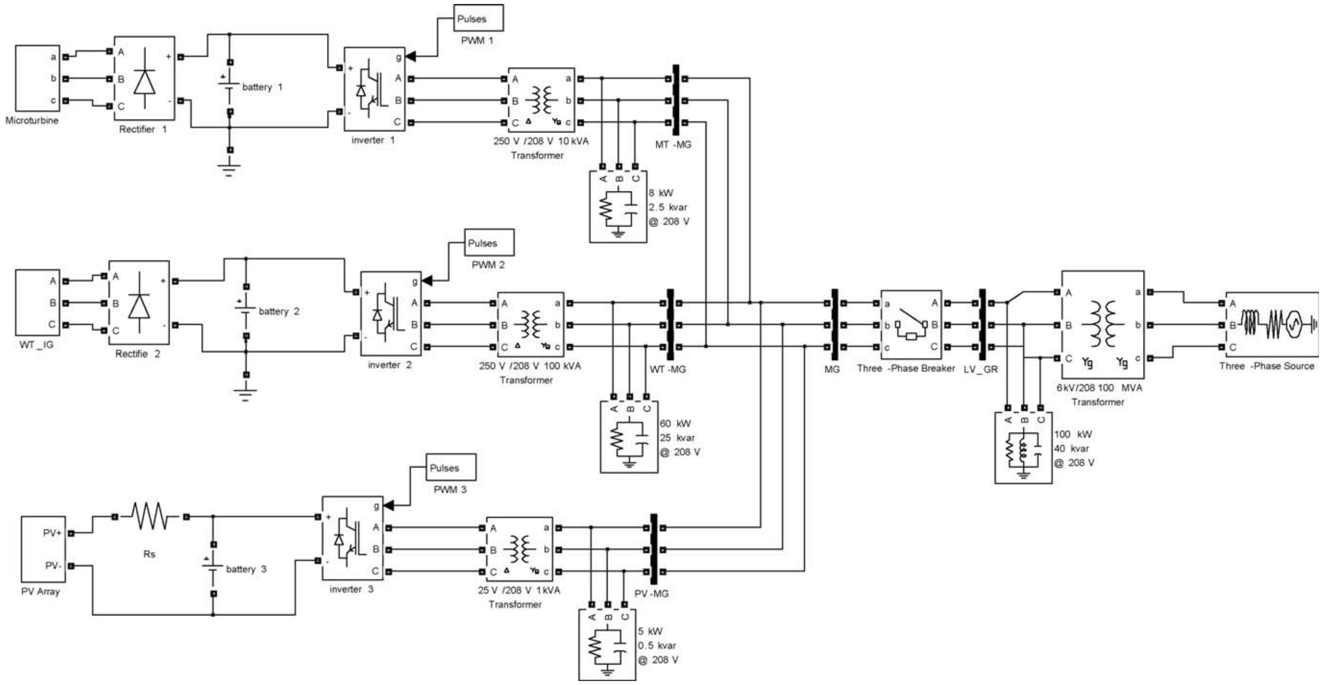

Fig. 6. Diagram of the case study system.

supplied by the grid. The reactive power loads are mainly used for voltage drop compensations and filters.

The simulation was conducted in Matlab/Simulink. The microturbine model is based on the Rowen model of gas turbine developed for biomass application in [51] with a scale-down capacity and high frequency application. The wind turbine model used in the simulation is the built in model in SimPowerSystem toolbox of Matlab/Simulink [52]. The PV array model is based on the PV behavioral model in PSpice [53] which was redeveloped in Matlab/Simulink [54].

The simulation was conducted to assess the basic operation of the system in islanded and gird-connected. First, the microgrid operates in islanded mode. After 0.5 s of the islanded operation, the breaker closes and the microgrid connects to the utility. For the grid-connected operation, both microgrid and utility must fulfill the following requirements:

- the voltage magnitude is equal,
- the frequency is equal, and
- the phase sequence is the same.

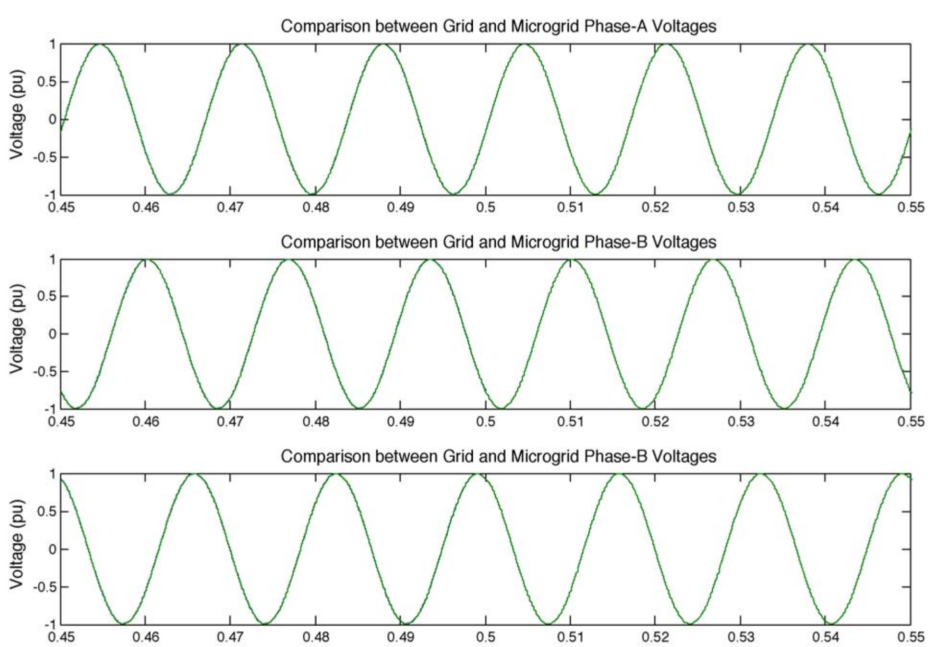

Fig. 7. Phase A, B, and C of the microgrid and grid voltages.

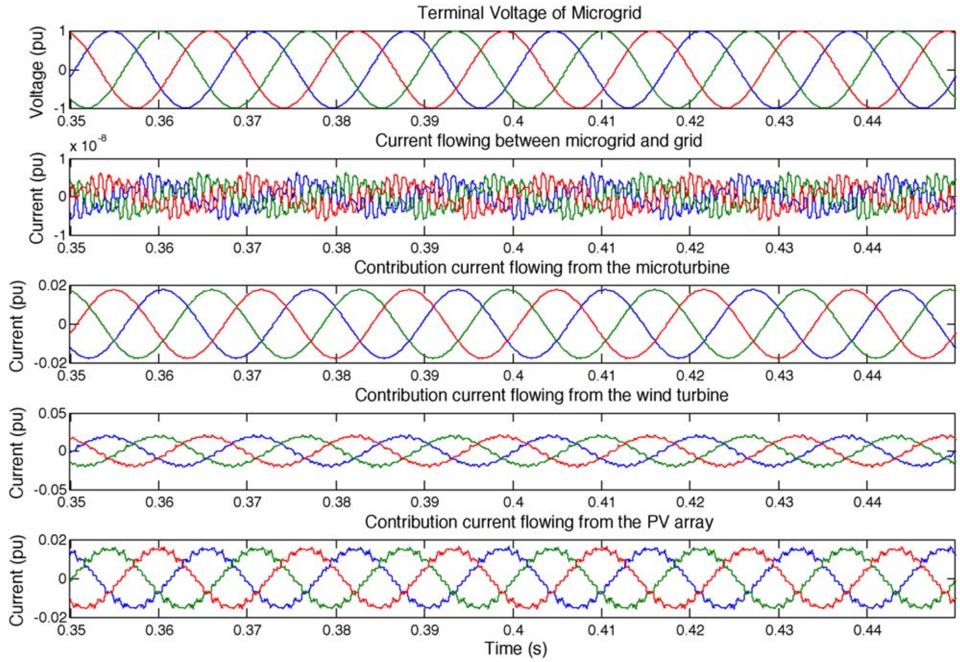

Fig. 8. Microgrid voltage and current and microsource contribution currents for islanded operation.

The simulation result in Fig. 7 shows sequentially the phase voltages of the microgrid and utility. The figure shows that the microgrid voltage and the utility voltage are overlapping. This means that the requirements for interconnection are satisfied.

The voltage and current of the microgrid for islanded operation, grid-connected operation, and around the breaker closing time are plotted in Figs. 8–10. In the islanded operation, the microgrid current, which is the current flowing between microgrid and grid, is negligible due to no connection between the microgrid and the utility. The microsource contribution currents are sinusoidal with small distortion. In the grid-connected operation, the wind turbine contribution current is unbalanced. Due to the big contribution of the wind power generation to the microgrid, this unbalance is also seen in the microgrid current. The most possible cause for this unbalance is transient due to the closing of breaker. Because the graph was plotted 0.35 s after the closing of breaker, this transient exists in the graph. In the closing time, the maximum overshoot of the currents was 5 pu.

The closeness of the voltage and currents plotted in the previous figures to sinusoidal can be assessed by using total

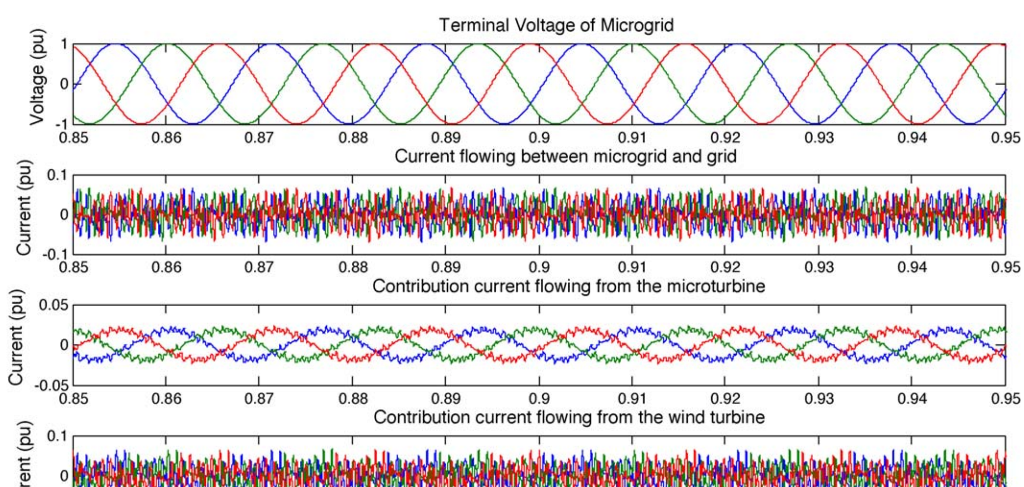

Fig. 9. Microgrid voltage and current and microsource contribution currents for grid-connected operation.

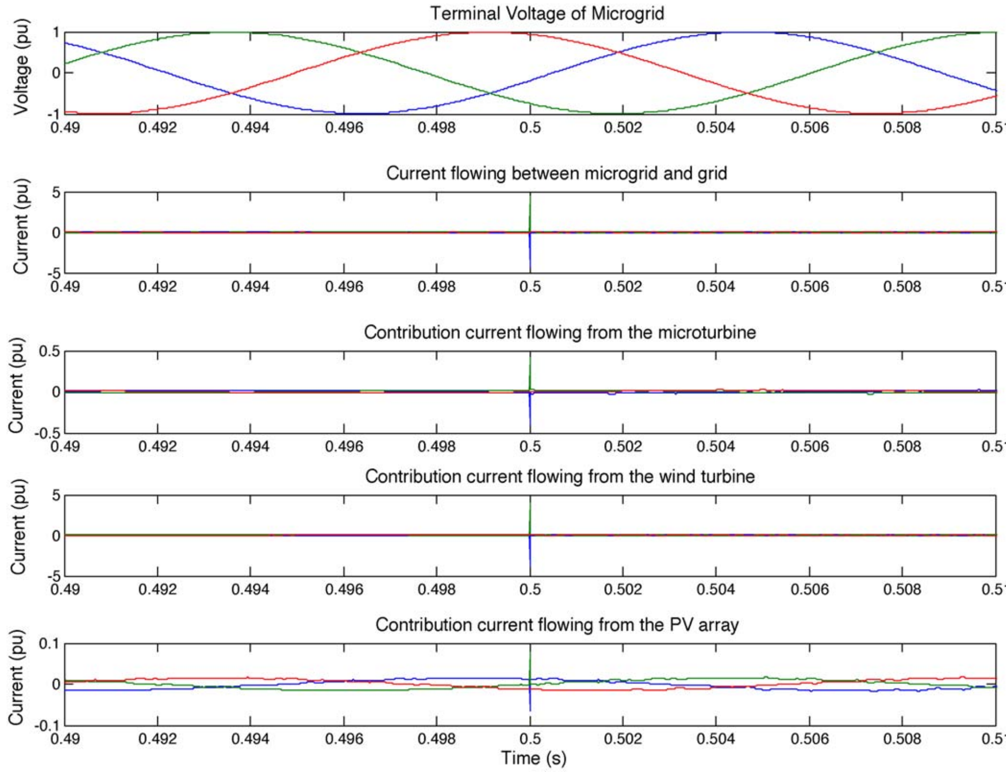

Fig. 10. Microgrid voltage and current and microsource contribution currents around the breaker closing time.

harmonic distortion (THD). THD is calculated by comparing rms value of harmonics to rms value of the fundamental component [55]. Figs. 11 and 12 show THD of the voltage and currents for islanded and grid-connected operation. THD of the voltage is less than 0.01% while THD of the currents are around 1%. It is obvious that the voltage and currents are very close to pure sinusoidal. The microgrid and contribution of the wind power generators currents also have very small THDs. This indicates that the current

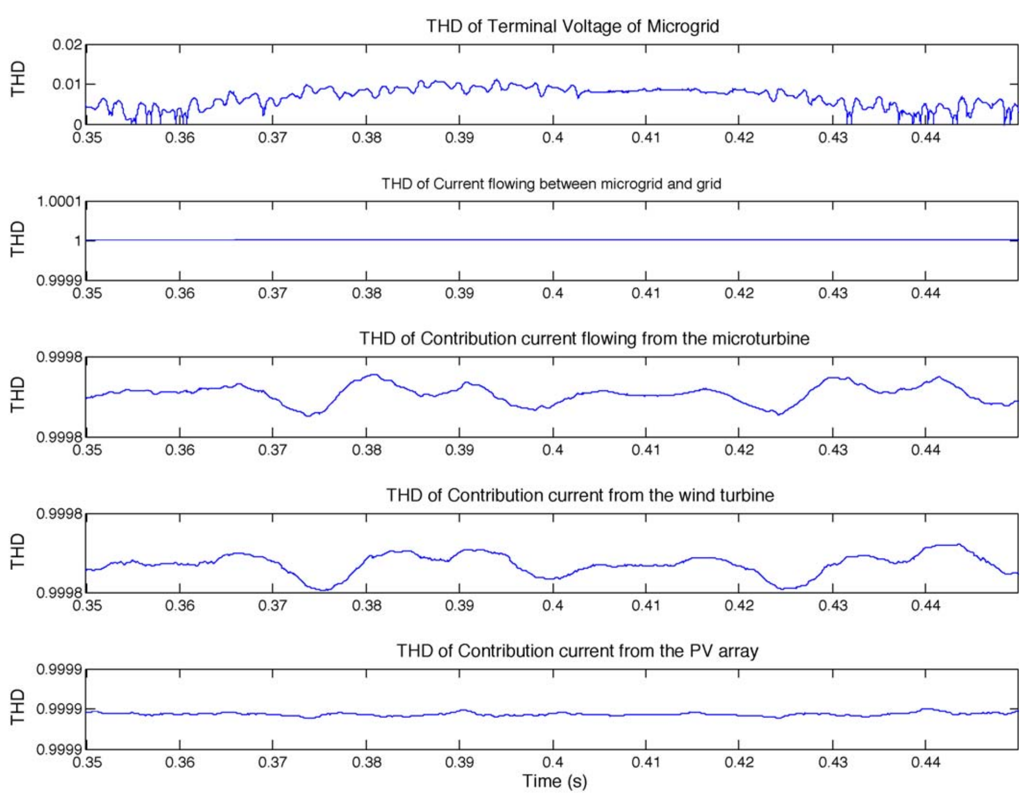

Fig. 11. THD of the microgrid voltage and current and microsource contribution currents for the islanded operation.

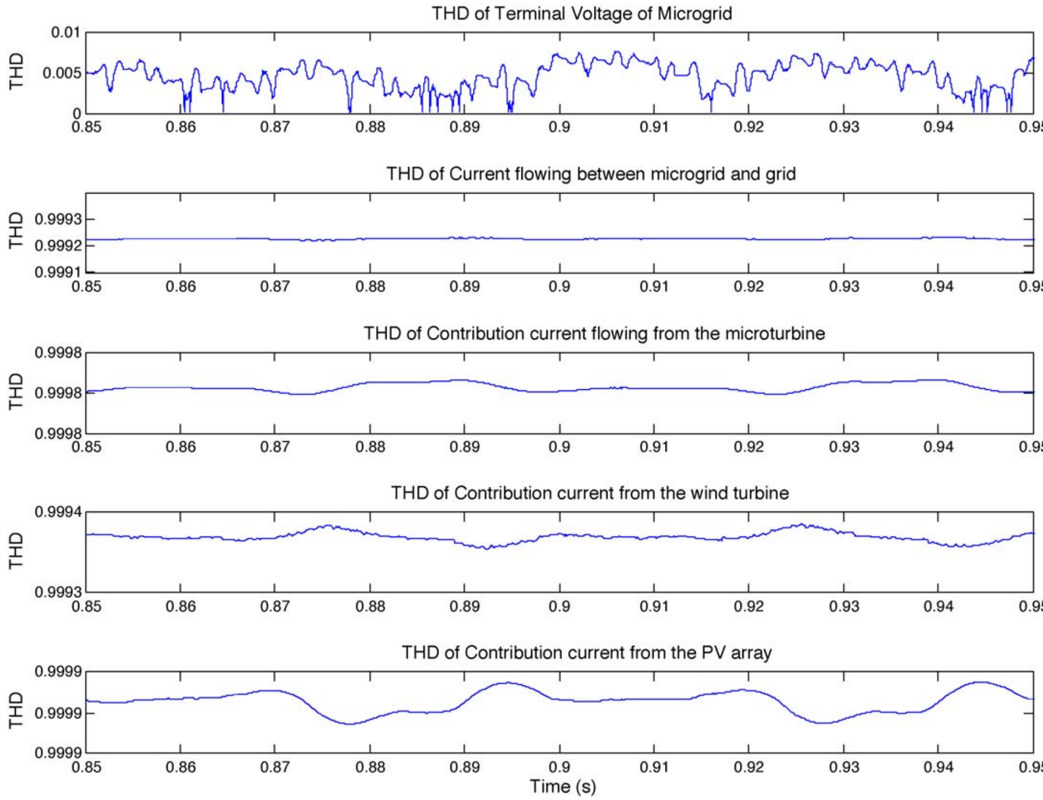

Fig. 12. THD of the microgrid voltage and current and microsource contribution currents for the grid-connected operation.

waveforms are very similar to pure sinusoidal while the three-phase waveforms are unbalanced. The balance condition will occur several second after the closing of breaker.

The simulation has been conducted to assess basic characteristics of microgrid either in grid-connected or islanded mode of operations. The microgrid components, microsources and loads, were sized to achieve the expected characteristics.

7. Conclusion

This paper has presented a comprehensive review of microgrid and discussed several aspects of controls, energy storage applications within microgrids and specific challenges. A case study simulation was conducted to evaluate the microgrid operation either in islanded or grid-connected systems. The simulation results shows that the microgrid improve reliability of the distribution system by providing power to the sensitive loads when there is no supply from the grid. Microgrid research fits very well with ongoing smartgrid activities through the world and several challenges need to be investigated before making it reality. Several research problems need to be solved in future to keep up with planned renewable energy integration in electric grid. Designing a multi-agent-based intelligent microgrid controller, self reconfigurable microgrid, handling inherent uncertainties of renewable sources, DC distribution based microgrids and hybrid distribution network for microgrids are few of the future research needs to support the future smartgrid system.

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